

# Fatigue Shear Strength of Slender Web Plate Girders

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## ABSTRACT

A study on the fatigue strength of slender web plates subjected to repeated shear loading is described herein. A series of tests on 20 girders with slender web was carried out. The girders were subjected to cyclic loading of a certain range up to the formation of fatigue cracking. Stresses along the welded connection between the webs and flanges were measured during the tests. The correlation between the stresses and number of cycles of loading at failure was analysed and a new fatigue resistant curve was developed and incorporated into the standard design curve of fatigue resistant given in BS 5400:Part 10 and EC 3:Chapter 9. The resistant to fatigue failure for the welded web under shear loading was found to be high compared to other standard detail categories.

## LIST OF SYMBOLS

$N_f$	Number of cycles to fatigue failure
$P$	Load
$\Delta\sigma$	Stress range
$\sigma_p$	Principal surface stress
$\sigma_b$	Principal secondary bending stress
$\sigma_m$	Principal membrane stress
$\sigma_{vm}$	von-Mises stress

## INTRODUCTION

Fabricated plate girders are used in road and railway bridges, and occasionally in building where heavy loads and /or large space are required. Its construction consists of three steel plates which are usually welded or bolted together to form the I-section. In recent time, numerous plate girders spanning 60 to 100 m have been constructed. With the introduction of automatic welding the cost of fabrication has been considerably reduced.

Prior to 1960, the design of plate girder webs was governed by elastic shear buckling, which generally imposed severe restrictions on plate slenderness. The development of ultimate limit state design methods in the early 1960's enabled the restriction on plate slenderness to be relaxed, when it was appreciated that a slender web can resist load significantly higher than its buckling load [1, 2].

In order to provide an efficient and economical girder design, advantage must be taken of the post-buckling capacity of the girder, i.e., its ability to carry loads considerably in excess of the buckling load. In this way, a girder of high strength/weight ratio can be designed, suitable for use in situations where reduction of selfweights is of prime importance such as in long span bridges, in aircraft and ship construction.

BS 5950 permits three options in the design of plate girders as is stated in Clause 4.5.5. Providing certain criteria are met, design can be based on shear buckling capacity only. To take advantage of tension field action design can refer to clause 4.5.5.3 which result in an increase in the allowable slenderness of web. Further refinement permitted by BS5950 is the use of full tension which take into account the additional contribution of rigid flanges, clause 4.5.5.4.

A problem associated with the behaviour of a slender web in the post-buckling state is the out-of-plane or lateral deflection of the web [2]. Under repeated loading, the behaviour has become known as plate breathing and plays major role in the fatigue deterioration of the web. The maximum secondary stress induced by plate breathing generally occurs along the weld between the web plate and boundary members. This is the most critical region for fatigue crack initiation.

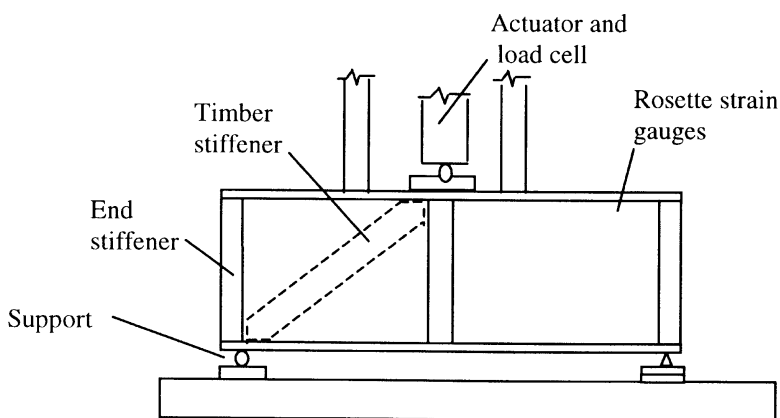
Experimental and theoretical study into the influence of plate breathing on the fatigue of slender web plates subjected to predominantly shear loading, has been carried out at the School of Engineering in Cardiff [3, 4, 5, 6].

Numerous tests have been conducted on simply supported, short span plate girders subjected to predominantly repeated shear loading, as shown in Figure 1.

The main objective of the test was to investigate the influence of combined membrane stresses and secondary bending stresses induced by out-of-plane web deformations during the post-buckling phase, on fatigue crack initiation and propagation. Measurements recorded during the tests included the out-of-plane deformations of the web panels, strains around the web boundaries, the rate of crack propagations and the final crack lengths at collapse.

## DETAIL OF TESTING PROCEDURE

Details of fabrication of all the test girders are presented in Table 1. The span to depth ratio of the girders was relatively very low, so that the web panels in each girder were loaded predominantly in shear. The width and thickness of the flanges were 250 mm and 10 mm for all girders. The flanges, central stiffeners and end stiffeners were oversized to ensure that the plate girders would not fail prematurely in an unforeseen mode. The test specimens were fabricated using grade 43 steel plate with the value of elastic Young Modulus obtained from coupon test was  $195 \text{ kN/mm}^2$ .



**Figure 1** Test rig for the fatigue test.

Strains in the web panels were measured using  $45^\circ$  strain gauge rosettes set at locations of predicted maximum stresses. The gauges were placed in pairs, one on each side of the web, so that membrane and bending strains could be deduced from the readings. Surface, membrane, bending, normal, shear and von Mises equivalence stresses are computed from the strain readings [7]. Von Mises equivalence stress is the measure of stress severity in a three dimensional state, in relation to the yield limit of the material [8]. The centres of the gauges were located 15 mm from the flanges and stiffeners, which was as close to the weld as it

was possible to place them. A dummy gauge, fixed to an unstrained piece of steel plate, was used to counteract strain variations due to temperature changes.

**Table 1** Fabrication details of the test girders.

Girder	Width of web (mm)	Depth of web (mm)	Web thickness (mm)	Flange thickness (mm)	Flange width (mm)
A	800	800	3	12	250
B	1200	800	3	12	250
C	1200	600	3	12	250
D	400	800	2	12	250
E1,E2	600	600	2	12	250
E3,E4	600	600	3	12	250
E5	600	400	2	12	250
E6	1200	800	3	12	250

Load was applied slowly, initially in increments of 25-50 kN and subsequently in smaller increments, up to the maximum applied load. After each load increment, a complete set of gauge readings was recorded and stresses around the webs were computed and plotted. This step was taken to make sure that the number and position of strain gauges were adequate to produce a good stress plot. It was also necessary to ensure that the loading did not cause excessively high stresses. Lateral web deflections were measured at zero and maximum load. The girders were then unloaded. A set of residual gauge readings was also recorded.

From the results of the static load test a suitable load range was chosen for the fatigue test, which would result in the required stress range in the web panel ie. principal surface stress range determined from strain gauge readings having a magnitude between 200 and 275 N/mm<sup>2</sup>. A sinusoidal dynamic load, having a frequency between 1.5 and 1.7 Hz (cycles per second) was then applied to the girder.

The test was stopped at intervals to record the gauge readings at maximum, minimum and zero load. The deflection cut out of the testing machine was set to 1 mm in excess of the current value at maximum load level, to prevent excessive deflection if a crack occurred during an unmanned session. Significant changes in the gauge readings generally indicated the initiation of fatigue cracking.

As well as the daily strain monitoring, the initiation of cracks was checked from time to time by visual inspection. Crack initiation was also detected by acoustic emission (AE) equipment, which monitored emissions between detectors at the corners of the girder.

Initial fatigue failure was defined as the development of a visual through crack in the web, about 100 mm long i.e. long enough to cause concern to practising engineers while allowing time for careful monitoring and repair prior to collapse.

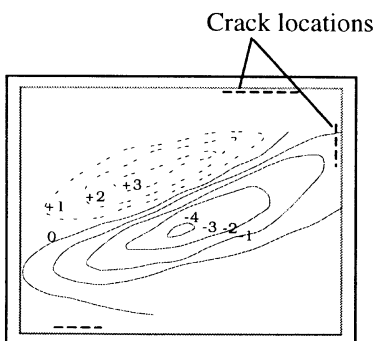
In large welded plate structures, residual stresses and stress concentrations due to geometrical details, welding irregularities and fabrication procedures, generally ensure that the upper limit of stress at potential fatigue crack locations is close to the material yield stress. Therefore, the applied stress range is the most significant parameter affecting fatigue performance, other parameters such as mean stress and material yield stress being of only minor significance.

## TEST RESULTS

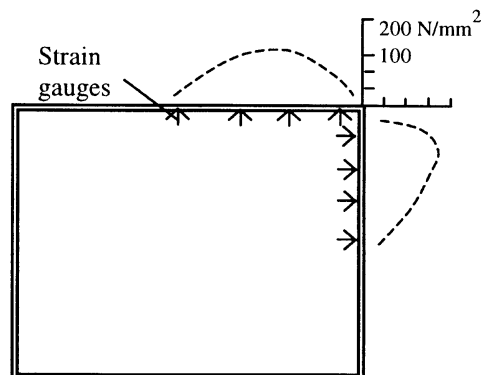
### Out-of-plane deformations of web panels

A typical contour plot of the initial imperfections and of the out-of-plane deformations corresponding to the maximum loads during the fatigue tests, is shown in Figure 2.

The initial imperfections of the web panels showed considerable variation in shape and maximum amplitude, which varied from approximately 1 mm to 6 mm. The buckled modes at the maximum loads during the fatigue tests, were fairly consistent for similar girders. Large shear buckles developed in the web panels, approximately in line with the tension diagonals.



**Figure 2** Out-of-plane deformation at maximum load.



**Figure 3** Stress distribution around the boundary.

During the tests, the webs of the test girders exhibited significant plate breathing, with pronounced shear buckles forming and reforming approximately in line with the tension diagonals during loading cycles. For geometrically similar girders, the post-buckling out-of-plane web deformations were reasonably consistent.

### **Stress ranges during the fatigue tests**

A typical plot of stress ranges (maximum stress minus minimum stress) around the web panel boundaries during the fatigue tests, is presented in Figure 3, which shows the ranges of principal surface, secondary bending and membrane stress. From these stress plots, the maximum stress ranges at the web panel boundaries were determined and incorporated in various  $\Delta\sigma-N$  plots.

As shown in the figure, the maximum secondary bending stress is slightly below the maximum surface stresses. The maximum values of these stresses occurred at a distance of approximately one third of the panel breadth from the tension diagonal corners. The membrane stresses were generally uniform around the web.

### **Fatigue crack locations**

The location of the fatigue crack is also shown in Figure 2. The fatigue cracks in all girders initiated close to the upper tension diagonal corner of the web plate, along the toe of the weld between the web plate and flange.

In general, the fatigue cracks initiated in regions of high secondary bending stresses, as indicated by the contour plots of the out-of-plane web deformations. This was also confirmed by plots of the secondary bending stresses along the web boundaries. The cracks formed along the toe of the fillet welds which were subjected to stress concentration due to the change in plate thickness.

**Table 2** Fatigue resistance based on different stress parameters.

Girder	$\Delta P$ (kN)	$N_f$ (cycles)	$\Delta\sigma_p$ N/mm <sup>2</sup>	$\Delta\sigma_b$ N/mm <sup>2</sup>	$\Delta\sigma_m$ N/mm <sup>2</sup>	$\Delta\sigma_{vm}$ N/mm <sup>2</sup>
A1	95	11000000	190	165	50	180
A2	188	353460	295	250	100	280
A3	160	905450	255	220	75	240
A4	105	1600000	210	195	65	220
B1	76	6022190	180	165	50	180
B2	107	1401620	215	200	40	200
B3	111	540740	255	233	50	230
B4	116	670190	295	270	50	300
C1	141	1339030	250	210	80	240
C2	145	487460	295	270	70	280
C3	144	1490230	220	190	43	220
D1	120	177000	300	280	110	330
D2	81	10000000	200	165	90	200
D3	105	445000	270	230	95	280
E1	62.5	1371530	205	170	85	230
E2	62.5	192470	275	225	125	300
E3	150	1352100	215	175	90	210
E4	160	1141500	280	175	170	340
E5	50	6951080	225	160	100	220
E6	112.5	2758300	210	190	70	190

$\Delta\sigma_p$  = Principal surface stress range       $\Delta\sigma_b$  = Principal secondary bending stress range  
 $\Delta\sigma_m$  = Principal membrane stress range     $\Delta\sigma_{vm}$  = von-Mises stress range

### Stress ranges and number of cycles to initial fatigue failure

In general, strains around the welded web boundaries were reasonably consistent, with the maximum at positions less than half way along the web boundary from the tension diagonal corner.

The load range and stress range applied and the number of cycles to fatigue cracking of all girders are summarised in Table 2. Load range  $\Delta P$  versus fatigue cycles  $N$  and stress range  $\Delta\sigma$  versus fatigue cycles have been plotted. However, the comparison showed that stress ranges offer a better basis for  $\Delta\sigma$ - $N$  relationships [4]. If the graph is plotted in normal scale, there is a significant scatter of results, which is characteristic of fatigue tests on large

welded plate structures. To reduce the scatter, the graph is plotted in log-log scale.

## DISCUSSION OF RESULTS

Analysis of strain gauge readings indicated a complex state of stress at the welded plate boundaries i.e. combination of surface stress, membrane, and secondary bending stresses. Statistical analysis have been carried out and the result is presented in graphically in Figure 4. In these figures, represents the range of maximum principal surface stress, secondary bending stress, membrane stress, von Mises equivalent stress respectively, determined from the stress plot presented in Figures 3. The detail categories for the highest and lowest fatigue resistant i.e. detail Class 160 and 36 respectively are also shown in Figure 4.

Statistical analysis indicates that the maximum principal surface and secondary bending stresses show close correlation with fatigue life, as is indicated in the statistical analysis result.

There are four  $\Delta\sigma$ - $N$  curves, based on the surface, secondary bending, normal and von Mises stresses, which exhibit close correlation with fatigue life. In practical, only one stress parameter is used to represent the  $\Delta\sigma$ - $N$  curve. BS 5400 fatigue assessment procedures are based on  $\Delta\sigma$ - $N$  curves which relate a geometric stress range  $\Delta\sigma$  to the number of cycles to fatigue failure  $N$ . Geometric stress is the maximum principal stress in the parent material, adjacent to the weld toe.

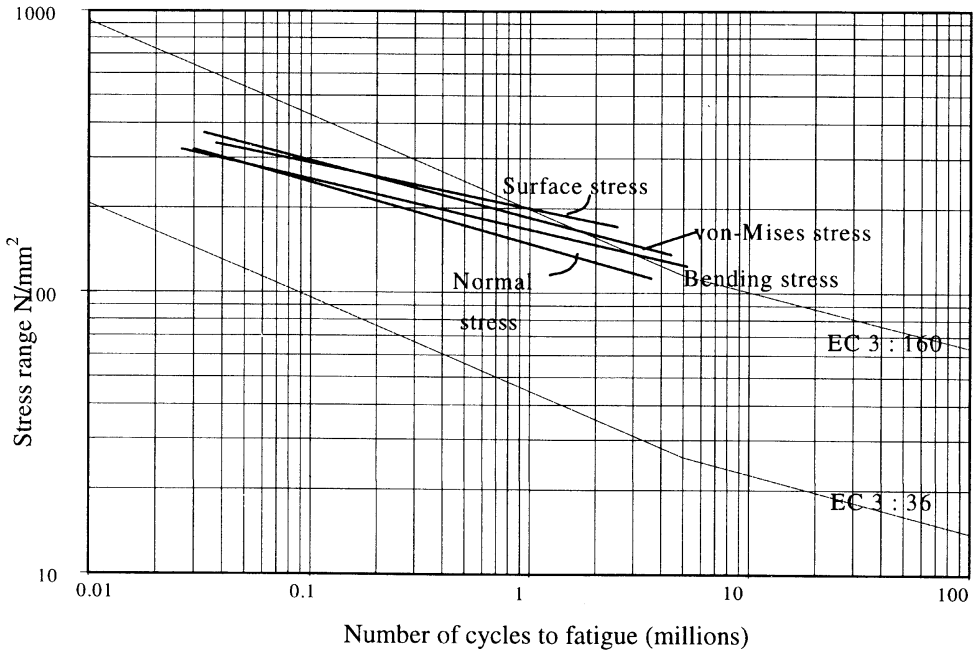
In the construction of experimental  $\Delta\sigma$ - $N$  curves,  $\Delta\sigma$  and  $N_f$  are plotted on logarithmic scales to reduce the scatter of experimental data and to yield straight line  $\log\Delta\sigma$ - $\log N$  relationships.

For the principal tensile surface stress range the linear equation of the mean regression line is

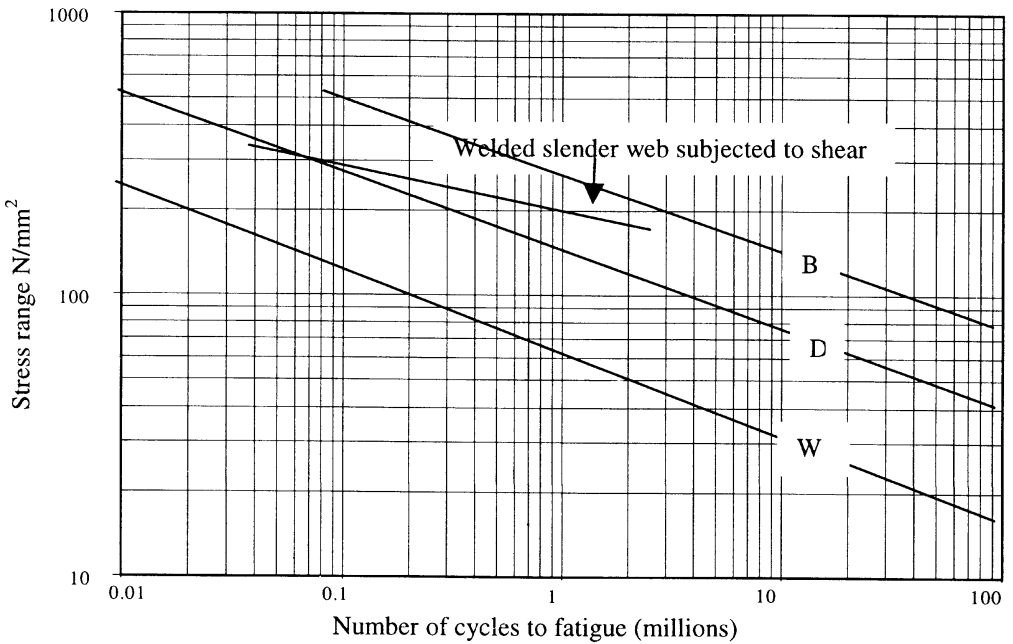
$$\log N_f = 20.79 - 6.17 \log \Delta\sigma \quad (1)$$

The lower bound 95% confidence limits for the principal stress ranges are compared with the BS 5400 detail category B to W (highest to lowest) fatigue strength curves, in Figure 5. The experimental results in this study indicates that the fatigue assessment of slender web plate girders may be based on a higher detail category fatigue strength curve. For stress ranges less than 300 N/mm<sup>2</sup>, which was the case for the majority of tests, it can be based on detail category class D in BS 5400.





**Figure 4** Fatigue resistance curve based on different stress parameters.



**Figure 5** Fatigue resistant curve for welded slender web under shear load, compared to the existing fatigue design curve in BS 5400.

## CONCLUSIONS

A series of static and fatigue tests has been conducted on six short span slender plate girders subjected to predominantly shear loading. Measurements recorded during the tests included the out-of-plane deformations of the web panels, strains at numerous locations around the welded web boundaries, the rate of crack propagations and the final crack lengths at collapse.

The most significant conclusions from the tests relating to fatigue life assessment are as follows:

- a) In general, fatigue cracks formed along the toe of the fillet weld between the web plate and boundary members, in regions of high secondary bending stresses. This was confirmed by the contour plots of out-of-plane web deformations and by the strain gauge readings.
- b) The number of load cycles to fatigue cracking decreased with an increase in the surface stress range. However, there was significant scatter in the test results which is typical of fatigue test results for large welded plate structures.
- c) The maximum principal surface stress can be used as the reference stress range in the construction of fatigue resistant design curve for slender web plate girder subjected to fatigue loading.
- d) For the stress range less than  $300 \text{ N/mm}^2$ , fatigue resistant design of slender web plate girder subjected to repeated shear loading can be based on detail category class D in BS 5400.

## REFERENCES

- [1] Yen, B. T. and Mueller, J. A., Fatigue tests of large-size welded plate girders, *Welding Research Council*, Bulletin No. 118, pp 1-25, (1966).
- [2] Porter, D. M., Rockey, K. C. and Evans, H. R., The collapse behaviour of plate girders loaded in shear, *The Structural Engineer*, Vol. 53, No.8, pp 313-325, (1975).
- [3] Roberts, T. M., Osman, M. H., Skaloud, M., and Zornerova, M., Fatigue crack propagation and residual strength of slender web panels, *International Colloquium on Stability of Steel Structures*, Budapest, 1995.
- [4] Roberts, T. M., Osman, M. H., Skaloud, M., and Zornerova, M., Residual strength of fatigue crack slender web panels, *Thin-Walled Structures*, 24, 1996.

- [5] Osman, M. H., Fatigue Cracking in Slender Web Plate Girders Subjected to Repeated Shear Loading, *Ph.D Thesis*, University of Wales Cardiff, 1996.
- [6] Bennet, R. H. , Fatigue Test on Slender Web Plate Girders Subjected to Repeated Shear Loading, *M.Sc Thesis*, University of Wales, Cardiff, 1995.
- [7] Dally, J. W. and Riley, W. F., *Experimental Stress Analysis*, McGraw Hill Book Company, pp 318-328, (1978).
- [8] Ford, H., *Advanced Mechanics of Materials*, Longman, 1966.